PROCEEDINGS, TOUGH Symposium 2003
Lawrence Berkeley National Laboratory, Berkeley, California, May 12–14, 2003

THE ROLE OF UNSATURATED FLOW IN ARTIFICAL RECHARGE PROJECTS

Alan L. Flint

U.S. Geological Survey
6000 J Street
Sacramento, CA, 95819-6129, USA
e-mail: aflint@usgs.gov

ABSTRACT

The hydrogeology of the unsaturated zone plays a critical role in determining the suitability of a site for artificial recharge. Optimally, a suitable site has highly permeable soils, capacity for horizontal flow at the aquifer boundary, lack of impeding layers, and a thick unsaturated zone. The suitability of a site is often determined by field and laboratory measurements of soil properties, field experiments, and numerical modeling.

An existing, but currently unused, artificial recharge site in the San Gorgonio Pass area in southern California, USA, was studied to better understand the role of the unsaturated zone directly beneath the site. Field measurements and observations were used to characterize the site and develop a conceptual model of the unsaturated zone. A numerical model was developed on the basis of the conceptual model and was calibrated using data from a 50-day artificial recharge experiment conducted in 1991. Results indicate that a restrictive layer exists 250 feet below land surface and will cause lateral diversion of the artificially recharged water, thus greatly reducing recharge to the water table 650 feet below land surface.

INTRODUCTION

Artificial recharge of water to an aquifer may be achieved by either surface spreading, injection in wells, or altering the natural conditions of stream channels to increase infiltration. Artificially recharged water must first move through the unsaturated zone, except for recharge using injection wells directly into an aquifer. For the most part, the unsaturated zone provides the underground storage space for recharge, although the amount of storage is dependent on the water retention characteristics and the natural recharge occurring at the site. The greater the natural recharge at a site, the greater the percent age of porosity that is occupied by antecedent water moving through the unsaturated zone, which results in a smaller amount of available space for the artificially recharged water.

The hydrologic properties of an unsaturated zone help determine the suitability of a particular location for artificial recharge. Optimally, areas used for artificial recharge should have highly permeable soils, the capacity for horizontal movement of water in the unsaturated zone and in the receiving aquifer, a lack of impeding layers, and a thick unsaturated zone. Under optimal conditions, water should reach the top of the saturated zone and spread laterally rather than building up a column of water toward the surface, which would greatly reduce recharge (Freeze and Cherry, 1979). The suitability of a site is often determined by field and laboratory measurements of soil properties, field experiments, and numerical modeling.

Several direct methods of artificial recharge commonly are used (Environmental and Water Resources Institute, 2001), including spreading basins and ditches for near-surface recharge applications, and pits and shafts for penetrating below near-surface restrictive layers. A third method, direct well injection into the unsaturated zone, is often used to penetrate below deeper restrictive layers. To highlight issues relating to the role of the unsaturated zone and unsaturated flow in recharging an aquifer, the following section discusses near-surface spreading basins being studied in the San Gorgonio Pass area in southern California.

SITE ANALYSIS

In 1991, spreading basins were used to test the feasibility of artificially recharging an aquifer in alluvial fans in Cherry Valley, which is in the San Gorgonio Pass area in southern California, (Shaikh and others, 1995). In 1997, the U.S. Geological Survey (USGS) was asked to evaluate the suitability of the unsaturated zone for artificial recharge and to develop models of the unsaturated and saturated zones of the San Gorgonio Pass area. Although well-organized guidelines are available for developing recharge spreading basins (Environmental and Water Resources Institute, 2001), spreading basins at this site were established in the 1960's prior to full analysis of subsurface hydrogeologic conditions and properties. Hydrogeologic data are essential in siting recharge spreading basins, particularly in alluvial basins where soils are highly stratified and contain continuous and discontinuous clay layers interbedded with sands and gravels (Flanigan and others, 1995).

As part of the USGS evaluation, several test wells were cored in the unsaturated zone and instrumented with deep tensiometers, heat-dissipation matric-potential sensors, temperature sensors, and suction lysimeters. Core samples and cuttings were analyzed in the USGS laboratory to determine particle-size distribution, water content, permeability, and lithology. An interpretation of these data suggests that there are several alternating high and low permeability layers between the surface and the water table (approximately 600 feet deep). A perched water table is present above a very low permeability layer 250 feet below the surface. Results of inverse modeling of borehole temperatures and water-level measurements, which show a slow decline in the water levels in the perched zone, indicates that the vertical hydraulic conductivity of the layer is less than 1 foot per year. Data from other boreholes in the area suggest that this perched layer is the top of an old, laterally extensive, geologic formation.

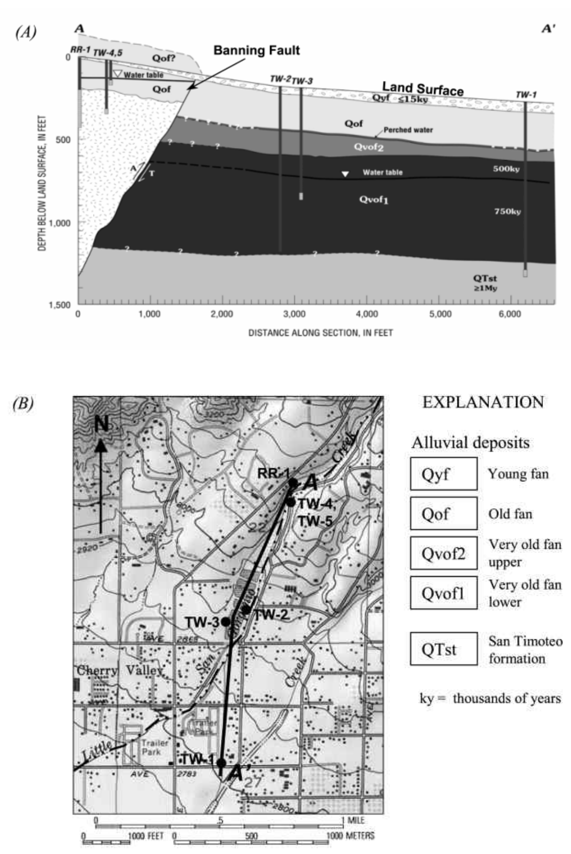

Figure 1. Conceptual cross section of the layered stratigraphy (A) and the relative location of the cross section and near-surface spreading basins to features of the San Gorgonio Pass area, California (B).

Surface-seismic and surface-resistivity measurements were used to develop a conceptual model of the layering and faulting in the area (fig. 1A). The existence of a shallow water table north of the Banning Fault suggests that the fault is a barrier to lateral flow. Temperature data from several boreholes in the area indicate that the coldest water in the unsaturated zone is the perched water. Temperature measurements made directly from flowing water in a nearby stream (San Gorgonio Creek, fig. 1) suggest that water in the perched zone is from local stream recharge and not from the shallow water table north of the fault, which supports the hypothesis that the Banning Fault is a barrier to flow.

NUMERICAL MODELING

The conceptual model of the unsaturated zone at San Gorgonio Pass was used for a numerical model of the unsaturated zone to further analyze existing data and to develop workable scenarios for artificial recharge. TOUGH2, an integrated finite-difference numerical code (Pruess and others, 1999), was used to develop the three-dimensional model. This code simulates the flow of heat, air, water, and nitrate (assumed to be present in septic tank leach fields) in three dimensions under saturated or unsaturated conditions. The geometry of the site requires a three-dimensional approach because of down-dip migration of recharged water through the alluvial fan deposits (north to south), as well as lateral flow of natural recharge (generally east to west) from the nearby stream. The modeling domain is approximately 1.6 miles (east to west) by 0.8 miles by 600 feet deep and contains more than 50,000 grid elements. The north and south lateral boundaries of the model are located along faults and are assumed no-flow boundaries. The east and west boundaries represent the edges of the alluvial basin where they encounter the mountain block. The bottom boundary is the water table and the upper boundary is specified flux. The surface flux is temporally and spatially variable depending on the artificial recharge scenario, and the location and amount of streamflow, septic tank return flow, and natural recharge from precipitation.

The model was initially developed using the hydrologic properties measured or estimated from the laboratory data. The model was further refined and calibrated by matching borehole temperature, matric potential data, and the occurrence of perched water. Borehole temperature data from 4 of the boreholes in figure 1 indicate a lower temperature zone at the perched water body in TW2 and TW3, and at the water table in TW1 and TW4 (fig. 2). TW4 is upgradient of the fault (fig. 1) and TW1 is down gradient and across a presumed fault between TW3 and TW1 (fig. 1; fault not shown). The cold temperature in the perched water body was used with the temperature profile under the perched water body to estimate the hydraulic conductivity of the perching layer. The hydraulic conductivity was estimated to be approximately 1E-3 m/d or 0.35 m/yr (fig. 3).

The only cold water source found in the study area was runoff from winter snow melt and cold winter precipitation (fig. 4). A 2-D cross section was simulated using the upper and bottom temperature boundary conditions and the temperature of the estimated stream recharge, 5 C. The results are in good agreement with the measured temperature data. The simulation shows a decrease in temperature from the ground surface to a minimum at the perched water body, then a gradual increase toward the water table (fig. 5). The simulated temperature at TW3 is warmer than TW2, which is consitent with the data because TW3 is further from the stream than TW2 (fig. 2 and fig. 5). In addition, the matric potential data was reasonably well matched to simulated matric potential as part of the calibration with the 2-D simulations (fig. 6).

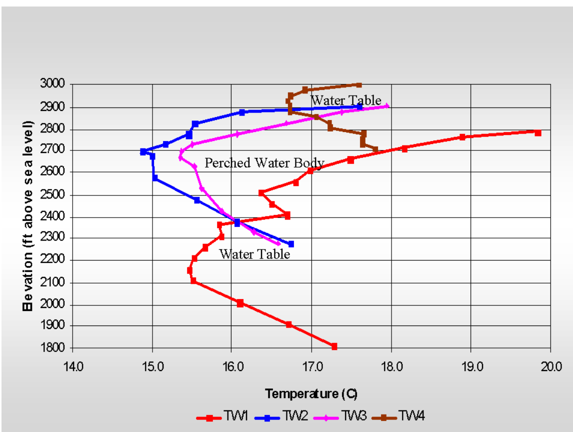

Figure 2. Deep temperature profiles from the four wells along the transect in figure 1.

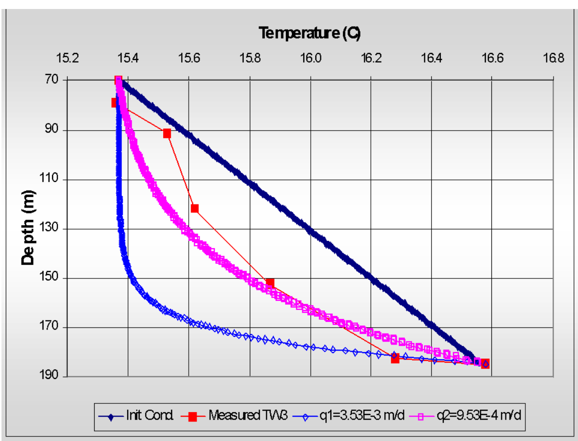

Figure 3. Measured and modeled temperature profiles below the perched zone.

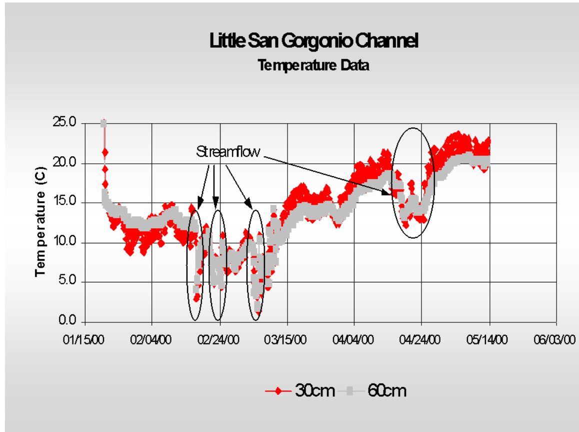

Figure 4. Stream temperature time series suggest possible source for cold water in perched zone.

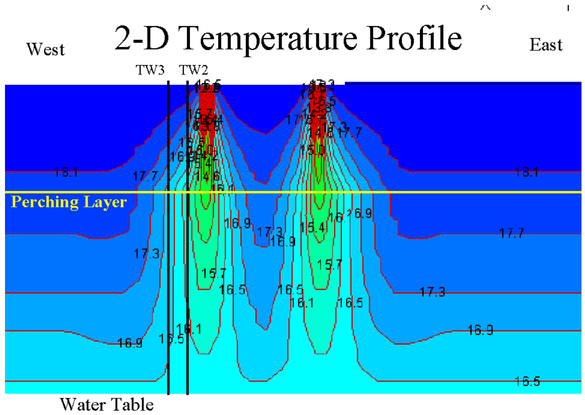

Figure 5. Simulated temperature profiles under two parallel streams show the decrease in temperature to a minimum at the perching layer then a gradual increase toward the water table, matching the response in TW3.

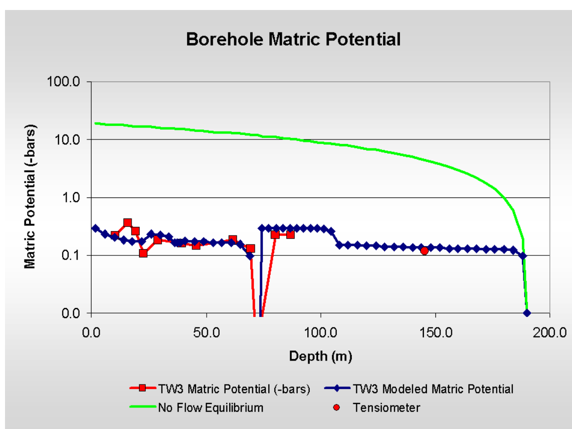

Figure 6. Measured and simulated borehole matric potential generated from the 2-d model results in figure 5.

The calibrated model was successfully used to simulate the observations made during the artificial recharge experiment conducted in 1991 and described by Shaikh and others (1995). Once calibrated, the model was run to steady-state conditions assuming natural recharge from precipitation and streamflow based on the results of the calibration of the saturated zone flow model. The model was then used to simulate historical and future artificial recharge conditions from 1950-2005. For the proposed artificial recharge scenario, 1,000 acre-ft of recharge was applied over a 50-day period each year from 2001 through 2005. The model simulation allowed comparison of measured and simulated data from 1991 to 2001, and predicted the response of the system to the proposed recharge scenario. The water content after 50 days of water application is shown in figure 7. In the simultion the application of water is discontinued for the remainder of the year with the exception of natural recharge. The second year of recharge is started and the results are shown 5 days into the second application in figure 8. The initial application has reached the perched water body and is moving downdip and backing up against the presumed fault (a no-flow boundary). By the end of the fifth year of simulation a considerable amount of water has accumulated against the fault (fig. 9). Matric potential, temperature, and pressure are shown in figure 10, 11, and 12, respectively, after the fifth year of application. The increased head in figure 12 against the fault suggests an approximate 45 m rise in the perched water that leads to increased percolation through the perching layers and can be seen as an increase in saturation below the perching layer (fig. 9).

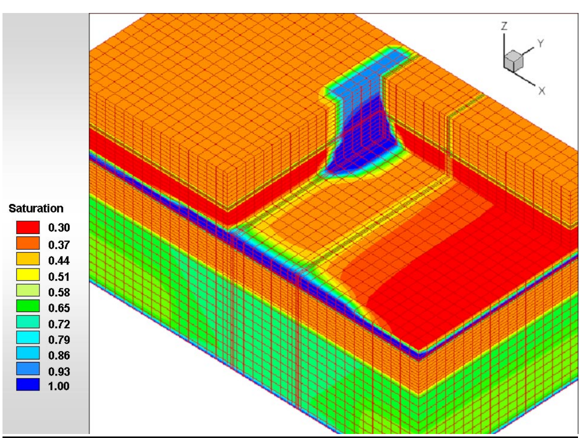

Figure 7. Simulation of water content after 50 days of application of water at recharge ponds during the first year.

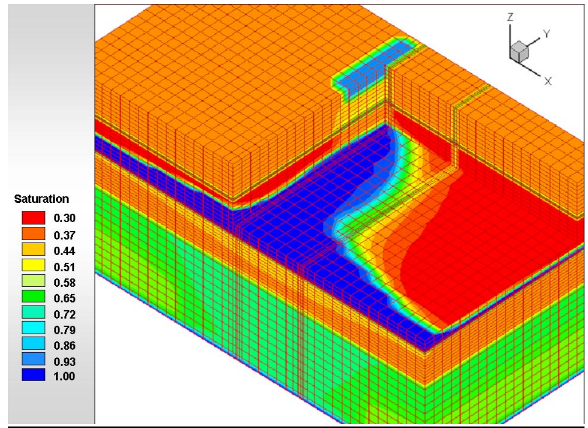

Figure 8. Simulation of water content after 5 days of application of water at recharge ponds during the second year.

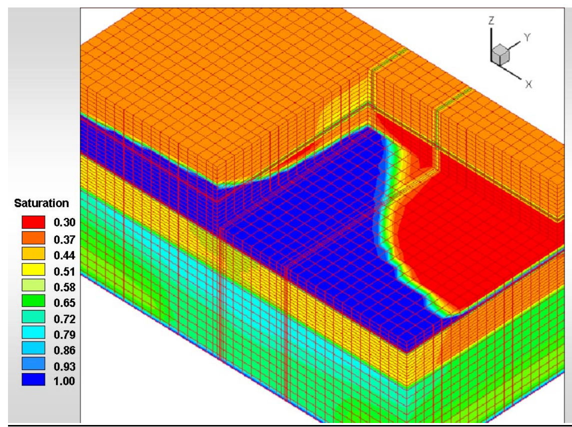

Figure 9. Simulation of water content after the fifth year of application of water at recharge ponds.

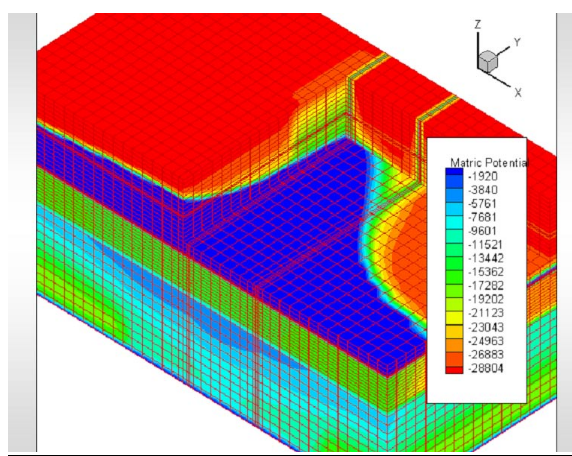

Figure 10. Simulation of matric potential in Pascals after the fifth year of application of water at recharge ponds.

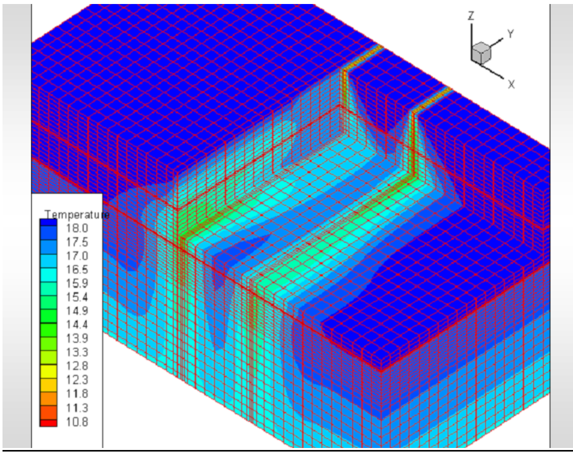

Figure 11. Simulation of temperature in degrees C after the fifth year of application of water at recharge ponds.

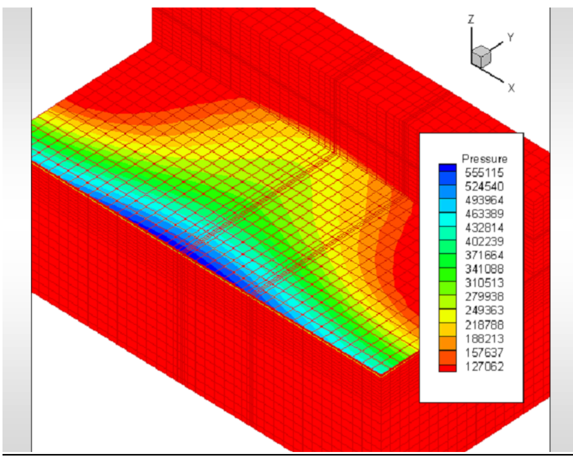

Figure 12. Simulation of pressure in Pascals after the fifth year of application of water at recharge ponds.

The model was used to simulate septic tank return flows that have 80 milligrams per liter nitrate-nitrogen (nitrate reported as nitrogen) during a proposed artificial recharge scenario. The model simulated 40 years of septic tank return flows before the artificial recharge scenarios were started. The artificially recharged water entrained some of the septic tank leachate and moved it below the perched water body after 4 years (fig. 13). The fresh water used in the simulation diluted most of the leachate near and around the recharge ponds.

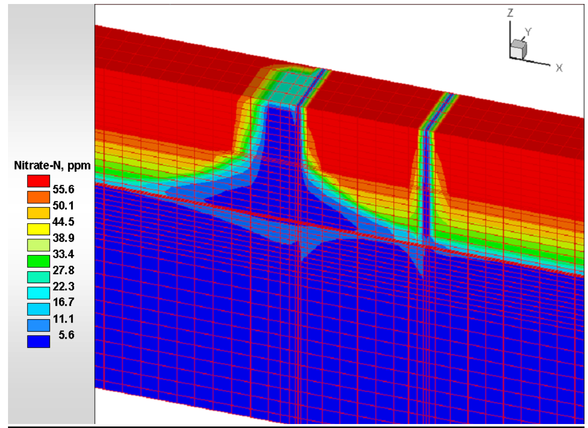

Figure 13. Simulations of nitrate as nitrogen after four years of accumulation under septic leach fields, followed by four years of artificial recharge.

Before the application of artificial recharge the simulated travel time from the surface to the water table was approximately 50 years for locations directly beneath the stream. Travel time increased to more than 250 years for locations away from the stream. The simulated addition of artificial recharge from 2001-2005 decreased the unsaturated-zone travel time to less than 10 years directly beneath the spreading basins and the travel time of the applied water that recharged the regional aquifer was less than 5 feet per year. The simulations suggest that little recharge will reach the regional water table under the spreading basin: furthermore, most of the artificially recharged water will remain above the perching layer at 250 ft below land surface, and will mound against the down-gradient no-flow boundary located about 4,000 feet south of the spreading basins. Although the recharged water intercepts nitrates from septic tank leach fields as it spreads laterally and vertically through the unsaturated zone, the simulated nitrate-nitrogen concentration of water in the perched water layer is less than 10 milligrams per liter, the maximum level set as a drinking water standard.

SUMMARY

Generally, artificial recharge projects apply water in surface and near-surface spreading basins, pits, and trenches, using the unsaturated zone to transport and store water. The hydrogeology of the unsaturated zone plays a critical role in transporting and storing artificially recharged water. Evaluating this zone will determine if the area is suitable for artificial recharge, and will help to identify the most effective methods of surface or subsurface application of water. Field and laboratory data and field experiments were used to develop a conceptual and a numerical model of the unsaturated zone at San Gorgonio Pass in southern

California. The results of the model simulations were used to refine the conceptual model and to test scenarios for artificial recharge. Results of the numerical model simulations of this site indicate that little recharge will reach the regional aquifer beneath the spreading basins, and that most of the water will remain above a perching layer at 250 feet below land surface, mound ing along the assumed no-flow fault boundary located about 4,000 feet south of the spreading basins. Further work on the characteristics of the fault and extension of the modeling domain further down gradient of the fault are required to provide more conclusive results for the characterization of the site for the application of artificial recharge

ACKNOWLEDGMENT

The San Gorgonio Pass Water Agency and Stephen Stockton, General Manager and Chief Engineer, supported this work.

REFERENCES

Environmental and Water Resources Institute, Standard guidelines for artificial recharge of ground water: American Society of Civil Engineers, Reston, Va., 106 p., 2001.

Flanigan, J.B., Sorensen, P.A., and Tucker, M.A., Use of hydrogeologic data in recharge pond design, vol. II *in* A.I. Johnson, and R.D. Pyne, eds., Artificial recharge of ground water: American Society of Civil Engineers, New York, p. 139-148, 1995.

Freeze, R.A. and Cherry, J.A., Groundwater: Prentice-Hall, Englewood Cliffs, New Jersey, p. 367-370, 1979.

Pruess, K., Oldenburg, C., and Moridis, G., *TOUGH2 User's Guide, Version 2.0*: Report LBNL-43134, Lawrence Berkeley National Laboratory, Berkeley, Calif., 1999.

Shaikh, A., Bell, R.B., Ford, M.E., and Stockton, S.P., Feasibility of recharge by surface spreading,:vol. II *in* A.I. Johnson, and R.D. Pyne, eds., Artificial recharge of ground water: American Society of Civil Engineers, New York, p. 159-167, 1995.